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Component Design Report: International Transportation Energy Demand Determinants Model

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Executive Summary

This *Component Design Report* discusses working design elements for a new model to replace the International Transportation Model (ITran) in the World Energy Projection System Plus (WEPS+) that is maintained by the U.S. Energy Information Administration. The key objective of the new International Transportation Energy Demand Determinants (ITEDD) model is to enable more rigorous, quantitative research related to energy consumption in the international transportation sectors.

A number of similarities will exist between the ITEDD and ITran models—for example, both models will provide measures of energy consumption by fuel type. However, ITEDD's design will differ from that of ITran in several key respects:

- Initial specification: A novel representational scheme will estimate travel demand, modal splits, and realized demand within ITEDD in a staged process that will be mediated by demand determinants such as vehicle stock availability. While many initial determinants will be estimated using current techniques, the new model will account for several new factors based on EIA's experience in modeling other sectors, such as accounting for unmet demand in the electric power sector.
- Demand determinants: The ITEDD model will consider a wider array of demand determinants than traditionally considered, such as population, income, industrial output, energy product trade, relative fuel prices, land use, infrastructure limitations, and policy measures. Careful consideration will need to be given to how the model interacts with other parts of the WEPS+ environment, including macroeconomic conditions across regions. Setting parameters for the model will also require more extensive and continual research than in the past.
- Calibration and integration: The ITEDD model will incorporate an iterative calibration procedure to refine the technical coefficients that account for developing trends in the demand for transportation fuels and related product volumes and prices. Energy demand and these and other related factors will be endogenously determined within the ITEDD model and the overall WEPS+ environment to the greatest extent possible. The new model will also effectively operate across a wide range of fuel supply and macroeconomic scenarios.
- Regional breakout: The ITEDD model will include a flexible regional design that allows us to consider important regional distinctions that may be identified in available data but are not considered in ITran. For example, travel behavior and fuel consumption in Chinese rural areas have a very different consumption profile than in urban areas. As a result, transportation demand in China is best modeled as two separate regions to properly account for the two distinctly different sets of consumption patterns.
- Policy study capabilities: The prototype version of the ITEDD model will be tested for the capability to incorporate and analyze a wide variety of policy and regulatory cases in a straightforward and transparent manner before the final model is implemented.

- Modeling platform: The prototype version of the ITEDD model will use the Python and Fortran modeling platform currently supporting WEPS+, although the decision for the modeling platform of the final ITEDD model is undetermined at this time.

Because the main goal of the project is to produce a model that is more robust, transparent, and accessible to modelers than ITran, a major challenge in the ITEDD model's development is adhering to this goal without sacrificing the detailed representation needed to accurately project international transportation fuel market dynamics.

Several of the elements included in the prototype version of the ITEDD model will rely on approaches currently used in the WEPS+ environment. These elements include the use of macroeconomic and historical fuel consumption data provided by other models in WEPS+. This approach is particularly true for fuels that are heavily linked to international trade, such as those used in marine transport. Future improvements made to other parts of WEPS+, such as a more robust representation of the international oil supply conditions, will be addressed during the finalization of the ITEDD model.

1. Overview

The main objective of developing the new International Transportation Energy Demand Determinants model is to construct and document plausible mobility scenarios that are consistent with different energy supply, demand, and economic growth scenarios. This *Component Design Report* describes the motivation for this project and explains why it is important. This report also discusses possible analytical approaches used to develop the new model.

Summary of Objectives:

- Simulate mobility scenarios that tell a story consistent with projected oil supply and price conditions and with projected economic growth conditions
- Include factors such as urban form, congestion, consumer behavior, and other key determinants of transportation demand as an integral part of the scenarios
- Forecast energy consumption in the transportation sector under a wide range of scenarios
- Analyze and illustrate the impact of various policy choices

2. Model Purpose

A Technical Requirements Analysis (TRA) was performed to consider the modeling needs and initial design considerations. This section summarizes the results of the TRA and the path chosen by the U.S. Energy Information Administration for the active development phase of the International Transportation Energy Demand Determinants (ITEDD) model.

2.1 Overview

The primary purpose of the ITEDD model is to provide projections of energy consumption across a wide range of mobility scenarios related to different energy supply conditions and rates of economic growth. The model will become an integrated part of the World Energy Projection System Plus (WEPS+) and provide sufficient detail to support a strong analytic basis for discussions on transportation demand in the *International Energy Outlook* and for special analyses on energy use in the transportation sector.

The top priority for model development is to provide projections for global liquid fuels consumption in relation to different rates of economic growth, fuel prices, and other important determinants of transportation demand. ITEDD does not need to provide detailed projections for countries that are not broken out as separate WEPS+ regions, modal or fuel choice for minor modes and fuels, or specific policies that are not implemented through sector- or economy-wide measures, such as taxes or technology standards. Some of this detail may be included, but these factors are not the primary goal or focus.

2.2 Capabilities

The ITEDD model will interact with other elements in the WEPS+ environment. In particular, the model will use fuel prices, energy commodity trade, and macroeconomic indicators from WEPS+ and will provide fuel consumption quantities for all projection periods to WEPS+ for use by the petroleum and other fuel supply models. The ITEDD model may also provide projected new vehicle sales and utilization of travel modes to WEPS+ for use in the macroeconomic model. These outputs will be presented in tabular form to assist in creating standard reports and special analyses.

These capabilities must be robust for a wide range of possible macroeconomic growth and fuel supply conditions.

2.3 Design

Scoping meetings and extensive research informed the design considerations for the development of the ITEDD model. As a guiding principle, the importance of global petroleum markets in large developing countries, such as China and India, was determined to be of high importance early in the model design process. The need to understand how demand is determined and the variability in outcomes was also identified as an important factor. As such, the need to represent determinants of demand that could alter the relationships between income, fuel price, and consumption is the primary motivation influencing the design requirement for the project.

The significance of capital investment for energy consumption makes it important to determine the level of technical detail related to capital stocks (e.g., vehicle types, rail, and public infrastructure) that should be included in the model. Even though the U.S. Energy Information Administration's analog to WEPS+ for the United States, the National Energy Modeling System, carries extensive detail on vehicle fleets, these data are not available for many regions of the world. The ITEDD model must account for the determinants of transportation-related energy consumption across all modes and regions, so it may need to consider how transport modes without direct capital stock measure interact with those with direct capital stock measures.

The existing WEPS+ environment also provides design requirements. The regional structure of WEPS+ is not absolute in that models can use different regions, but the related models are based on a consistent set of regional definitions to communicate with one another. For example, if the ITEDD model includes individual regions in China, it must also produce a number of initial estimates for the entire country to interact with other models during the process of converging to a global solution.

Not all major variables must be provided at the regional level. The fuel supply models in WEPS+ require fuel quantities in specific units, but these quantities do not necessarily need to be provided at the detailed regional level. If this detail is provided, the values across regions need to be cumulated to a world demand total. This requirement makes it necessary to determine where in the overall WEPS+ structure the summation of world fuel demand will take place. Similarly, the Oxford Economics model[1] used for macroeconomic projection has regional and industry-specific structure for which the ITEDD model will need to interact.

Finally, the ITEDD model will operate across a wide range of macroeconomic and fuel supply conditions. Because these conditions have substantial uncertainty, the model should allow users to see, understand, and affect the dynamics governing the projected outcomes when economic or price conditions vary substantially across regions or case studies.

2.4 Special studies

The ITEDD model has a wide range of potential topics to analyze. Therefore, we must identify the model's capabilities and limitations so that we can understand the applicability of the ITEDD model to specific studies.

First and foremost, the design requirements must enable a robust baseline for the most common set of projections within the current WEPS+ framework. However, many international transportation issues may require special analysis. Possibilities include the effectiveness of policies favoring mass transit or specific technology improvements. The level of detail in capital stock representation is most likely to be the determining factor for the ITEDD model's analytic suitability in analyzing many of these issues.

[1] See Oxford Economics, *Global Economic Model*, June 2015, website www.oxfordeconomics.com (subscription service).

To the extent that greater detail in capital stock representation can be developed, without compromising the core functionality of the system, such detail would open up additional analytic topics for consideration.

Expanding the capital stock representation by mode and region would also be desirable for the ITEDD model. Future versions could have more modes and regions represented by capital stock characteristics (e.g., vintage, efficiency, cost, quality) that enable more detailed studies.

2.5 Software

Within the overall field of computer simulation modeling, the design requirements for ITEDD present no particular challenges. The data arrays, algorithms, and iterative solution processes called for are typical of most dynamic simulation models. Because we can use a wide variety of software packages, broader considerations governing software selection, such as cost, ease of use, and desire for a common modeling platform, should drive the selection.

3. Background

The modeling system used to produce the *International Energy Outlook* is the World Energy Projection System Plus (WEPS+). WEPS+ is based on a number of models that are each developed independently and then joined to communicate with one another through a common database to find a universal solution. The models are dynamic, and the system uses an iterative solution technique to allow the models to converge on an equilibrium set of simultaneous market clearing conditions.

WEPS+ begins by running a set of detailed models before a main model is run to determine the direction of changes needed in the variables included in each of the more detailed models to move closer towards global convergence. One complete set of model runs, which concludes with the main model, is called an iteration.

Convergence often requires several iterations as the system searches for the appropriate set of market clearing conditions across all models. WEPS+ also allows for individual models to be run outside of the iterative process. A model run before the iterative process has begun is called a *preprocessor* and is typically used to establish initial conditions. A model run after the iterative process has finished is called a *postprocessor* and is typically used for writing reports.

3.1 Current approach

The current WEPS+ Transportation Model, also referred to as the International Transportation Model (ITran), projects the energy consumed in the provision of passenger and freight transportation services. These services include household on-road transportation in light-duty vehicles (LDVs), so the related energy consumption is accounted for separately from household consumption. The model projects consumption for a number of energy sources in each of the 16 WEPS+ regions through the year 2040. However, by the time the ITEDD model is finalized, WEPS+ is expected to project energy consumption through the year 2050.

ITran provides an accounting framework for projecting both the level of travel and the energy consumed in the provision of travel services. The model categorizes transportation services for passengers and freight into four separate modes including separate transportation services (Table 1).

Table 1. Transportation submodes included in the ITran model

Transportation Modes	Transportation Submodes
1. Road	1a. Light-Duty Vehicles
	1b. 2- and 3-Wheel Vehicles
	1c. Buses
	1d. Freight Trucks
	1e. Other Trucks
2. Rail	2a. Passenger
	2b. Freight Coal (Placeholder)
	2c. Freight Other
3. Water	3a. Domestic
	3b. International
4. Air	4a. Passenger Air
	4b. Freight Air (Placeholder)

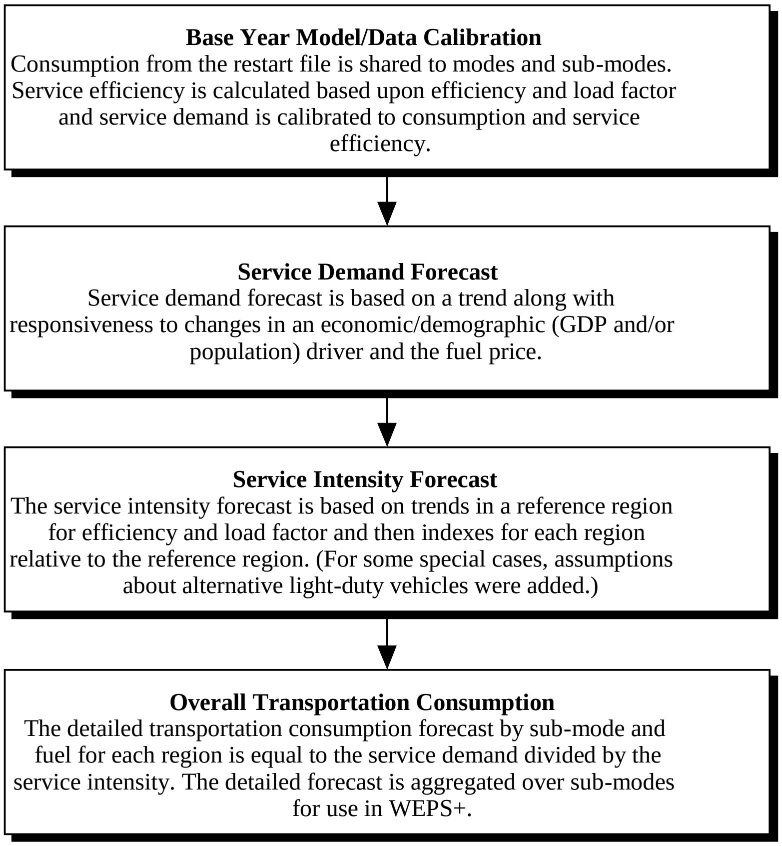
Source: U.S. Energy Information Administration, *Transportation Model of the World Energy Projection System Plus 2011*, Table 1.

Services in the model are measured in units of passenger-miles for each of the passenger services and ton-miles for each of the freight services. The model uses generic fuel categories to represent the efficiency with which each vehicle type provides the service. The average characteristics of each fuel category may change over the forecast by user assumption, but the model does not track the stock or vintage of vehicles (Figure 1).

The model is based on two measurement concepts: service demand and service intensity. In the case of passenger modes, service demand is measured in passenger-miles, and service intensity is measured in terms of passenger-miles per British thermal units (Btu). In the case of freight modes, service demand is measured in ton-miles, and service intensity is measured in terms of ton-miles per Btu, which means that consumption for each mode is calculated by the following equation:

$$QtyBtu = ServiceDemand / ServiceIntensity$$

Figure 1. Major ITran functions



Source: U.S. Energy Information Administration, *Transportation Model of the World Energy Projection System Plus: Model Documentation 2011*, Figure 8.

Service Intensity. The forecast of service intensity (TrnSI) is specified exogenously in several variables. First, it is expressed as two components for the base service intensity and for the load factor. Each of these is, in turn, specified as a reference starting point with regional indexes and as a reference forecast with regional indexes. For example, the service intensity forecast for each service, fuel, and region is given by the following equation:

TrnSI(s, f, r, y) = BYRefServ(s, f) * FYRefServEFM(s, f, y) * FYRefServLDM(s, f, y) *

FYRegServEFM(s, f, r, y) * FYRegServLDM(s, f, r, y)

where

$BYRefServ$ is the beginning year reference service intensity (SI),

$FYRefServEFM$ is the forecast year reference efficiency multiplier for SI,

$FYRefServLDM$ is the forecast year reference load multiplier for SI,

$FYRegServEFM$ is the forecast year regional efficiency multiplier for SI, and

$FYRegServLDM$ is the forecast year regional load multiplier for SI.

All of these exogenous pieces are multiplied in the model to arrive at a measure of service intensity. However, in the ITEDD model, the regional factors will be multiplied outside the model and input as an efficiency piece and as a load factor piece, except for LDVs, where efficiency will be determined endogenously within the model.

The service intensity elements are specified and input into the model over the forecast period at five-year intervals. As it turns out, in almost all cases the pattern of service intensity elements is linear. However, in the ITEDD model, each element will be represented as an input with a starting point and a slope. This method reduces the number of inputs, and makes them more transparent and easier to change and fine tune.

Service Demand. The starting point for service demand is determined by using consumption and service intensity to solve for the service demand. The forecast of service demand for each service is then based on an elasticity related to overall economic activity or demographics, such as gross domestic product (GDP), per capita GDP, or population, and an elasticity for price. In some cases, a linear extrapolation of economic growth may be used instead. The method used depends on data availability. Service demand is then parsed out across fuels based on exogenously-determined fuel shares.

The elasticities are specified for each five-year period but are generally consistent over time. In the new model, they will be represented and input as a starting elasticity and a slope. The service demand shares are specified, and each are input for every five years but are generally constant over longer time horizons. However, in the ITEDD model, the shares will be represented with an initial starting value input and slopes over time, and all shares will be normalized to add up to 1.0 in each projection year.

Transportation Modes. *Road mode* is disaggregated into light-duty vehicles (LDV), 2- and 3-wheel vehicles, buses, other trucks, and freight trucks. *Rail mode* is disaggregated into passenger, coal freight, and other freight submodes; however, the model does not actually address coal freight. *Air mode* is disaggregated into passenger and freight submodes, but nothing is actually done with the passenger category. *Water mode* is disaggregated into domestic and international submodes.

3.2 Other approaches

Previous approaches to model energy in the transportation sector can be grouped into five different categories—structural, accounting, linear optimization, computable general equilibrium, and hybrid models.

3.2.1 Structural models

Time series models have been used to estimate the lag structure and influence of various factors on transportation demand. For example, most studies find that increases in per capita income typically have a small short-run[2] effect on the demand for light-duty travel and a larger long-run[3] effect as capital stocks are able to evolve over time. These estimated relationships are then used to parameterize a structured model based on a system of equations to forecast future activity.

Many structural models based on the statistical approach do not explicitly account for the development of infrastructure and the evolution of capital stocks that may relax many of the short-term constraints on consumption. Even though these models are often appropriate for short-term forecasting, they are less appropriate in providing long-term projections. These models often tend to be parsimonious in nature and developed with a different goal in mind.

Models designed to provide long-term projections circumvent some of this generalization by considering much more detail, such as stock-flow accounting identities, engineering equations, and a more sophisticated set of parameterized equations to capture factors that influence market development over a longer time horizon. Because government policies often target the development of cleaner, more fuel-efficient vehicles or the use of different types of public infrastructure, assumptions concerning how a region’s transportation infrastructure will evolve are best left explicit in the ITEDD model.

3.2.2 Accounting models

The International Energy Agency developed a spreadsheet modeling tool called the Mobility Model (MoMo).[4] MoMo input and solution methodology is based on measured relationships between gross domestic product and population growth, fuel economies, costs, travel demand, vehicle stocks, and fuel market shares. The tool is organized around four OECD (Organization for Economic Cooperation and Development) regional clusters and 11 groups of non-OECD countries.

MoMo inputs include technologies and fuel pathways and provide the full evaluation of the life cycle of greenhouse gas (GHG) emissions, cost estimates for new LDVs, estimates for fuel costs and taxes, and the intermediate inputs required for LDV production.

[2] The short run is typically defined as a length of time in which the stock of vehicles and public infrastructure imposes a constant on growth.
[3] The long run is defined as a time frame in which there are no constraints related to fixed capital.
[4] See International Energy Agency, *Modelling of the transport sector in the Mobility Model (MoMo)*, http://www.iea.org/etp/etpmodel/transport/.

Table 2. IEA Mobility Model transport modes and fuel pathways

Category	Mode, Technology, or Fuel	
Modes	2- and 3-Wheel Vehicles	
	Light-Duty Vehicles	Spark Ignition (SI) ICEs[a]
		Compression Ignition (CI) ICEs[a]
		SI Hybrid ICEs (including plug-ins)
		CI Hybrid ICEs (including plug-ins)
		Hydrogen ICE Hybrids (including plug-ins)
		Fuel Cell Vehicles
		Electric Vehicles
	Heavy-Duty Vehicles	Minibuses
		Buses
		Medium Freight Trucks
		Heavy Freight Trucks
	Rail (passenger and freight)	
	Air	
	Water Transport (national and international)	
Fuel Pathways	Motor Gasoline	
	Diesel (high- and low-sulphur)	
	Ethanol	
	Biodiesel	
	Gas to Liquid (GTL)	
	Coal to Liquid (CTL)	
	Compressed Natural Gas (CNG)	
	Liquid Petroleum Gas (LPG)	
	Hydrogen	
	Electricity	

[a] Internal combustion engines

Source: International Energy Agency, "The IEA Mobility Model," slides 4 and 5.

MoMo is based on a well-known decomposition for transportation demand known as the *ASIF* framework[5], which is expressed in the following equation:

Activity (passenger travel) * Structure (travel by mode, load factors) * Energy Intensity = Fuel Use.

The system tracks a number of different interrelated measures, depending on vehicle type and mode of transport (Table 2):

- **LDVs and freight trucks**. Stock and sales by model; activity, intensity, and energy use; carbon dioxide emissions on a well-to-wheel and a tank-to-wheel basis; pollutant emissions (carbon

[5] See IEA's *Modelling of the transport sector in the Mobility Model (MoMo).*

monoxide, volatile organic compounds, particulate matter, lead, and nitrogen oxide), and fuel and vehicle costs.

- **Busses and other 2- to 3-wheel vehicles**. Stock, stock efficiency, energy use, and emissions.
- **Rail and air**. Total travel activity, energy intensities, energy use and emissions.
- **Shipping.** Sectoral energy use and emissions.[6]

This framework is most suitable for user-generated sensitivity analysis to facilitate an understanding of how other measures are likely to change based on an initial change in one of the other measures.

This ASIF framework has strengths and weaknesses. It contains a wealth of detail, but the dynamics governing the evolution of the measures accounted for in the system are not transparent. In addition, the need for user inputs makes scenario development highly dependent on analytical skill and judgment.

MoMo was used for IEA's *Energy Technology Perspectives* publication in 2012, which focused on how to get to a low carbon dioxide world in light of the important role of technology[7]. The system also provides primary input for the model used to develop IEA's *World Energy Outlook.*

Another example of the accounting approach is the Global Roadmap Transportation model[8] developed by the International Council on Clean Transportation to analyze potential growth in transportation energy use and emissions and the impacts of related energy policies. The spreadsheet covers 16 regions and most transportation modes, including LDVs, buses, 2-wheel vehicles, 3-wheel vehicles, light heavy-duty trucks (HDTs), medium HDTs, heavy HDTs, passenger rail, freight rail, passenger aviation, and marine freight. For most of the on-road travel modes, a stock accounting model is used for estimating average efficiency based on user-specified new vehicle efficiency. This model projects growth in passenger- and freight-ton kilometers resulting from growth in GDP and population.

3.2.3 Linear optimization models

Linear optimization models attempt to minimize the cost of energy services by selecting the optimal level of various technology options to meet a certain level of transportation demand determined outside the model. Transportation services are measured by passenger-miles or vehicle-miles or kilometers and freight ton-miles. Intermodal substitution is also often not represented in these models. These challenges can be a major concern in international modeling efforts because of the high degree of uncertainty associated with how transportation demand will be met in many developing countries.

One of the best known groups of optimization models includes the Market Allocation (MARKAL) model and The Integrated MARKAL-EFOM System (TIMES) model. These models can be used at the country

[6] IEA, "The IEA Mobility Model," slide 9, slide presentation accessed at http://www.slideshare.net/internationalenergyagency/iea-mo-mopresentation.
[7] IEA, *Energy Technology Perspectives 2012: Pathways to a Clean Energy System*, https://www.iea.org/publications/freepublications/publication/ETP2012_free.pdf.
[8] See the International Council on Clean Transportation's *Global Transportation Roadmap: Model Documentation and User Guide*, ICCT Roadmap Model Version 1-0, December 2012.

level or on a global scale and generally include all sectors of the energy economy. These models all solve intertemporally for the optimal solution for a universal objective function.

While the IEA uses the TIMES modeling framework in its ETP model, transportation energy is projected through a link to MoMo. As IEA's website indicates, "For the end-use sectors (buildings, transport, and industry), doing a pure least-cost analysis is difficult and not always suitable."[9] Several MARKAL/TIMES models have been used to examine the potential transition to hydrogen fuel cell LDVs, which requires modeling infrastructure build-out as well as representation of consumer behavior for vehicle purchases. One such study[10] pointed out the importance of vehicle segmentation and the imposition of constraints on technology shares by segment. In linear programming models, the lowest-cost technology will tend to achieve 100% market share unless constraints are imposed.

3.2.4 Computable general equilibrium (CGE) models

These models are based on the relationships between sectors typically measured in an input-output (I-O) table. Unlike I-O models where these matrixes are simply inverted and multiplied by an initial change to measure impacts across all sectors, CGE models include econometrically estimated elasticities that allow these historical relationships to change as the economy reacts to a large initial change. CGE models often include measures of physical quantities as well as the total value of output. One drawback with CGE models, however, is that they lack the industry detail provided in an I-O model.

Two CGE models that include a somewhat detailed transportation sector are the Dynamic Integrated Economy/Energy/Emissions Model, which was developed at the Nicholas Institute for Environmental Policy Solutions at Duke University,[11] and the MIT Emissions Prediction and Policy Analysis Version 5 model.[12] The Massachusetts Institute of Technology also developed a global model with 30 regions for China called the China Regional Energy Model.[13] In all three of these models, household transportation demand is shared between personal vehicles and purchased transport. Energy efficiency opportunities in LDVs are also represented. However, freight travel is often tracked in total value rather than in physical units and not split between road and non-road categories.

3.2.5 Hybrid models

As described by the Joint Climate Research Institute, "GCAM is a dynamic-recursive model with technology-rich representations of the economy, energy sector, land use and water linked to a climate

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[9] IEA, *Energy Technology Perspectives*, https://www.iea.org/etp/etpmodel/ (accessed August 2016).
[10] Dodds, Paul and Will McDowall, "Methodologies for Representing the Road Transport Sector in Energy System Models," *International Journal of Hydrogen Energy*, No. 5 (2014) (accessed doi:10.1016/j.ijhydene.2013.11.021 August 2016).
[11] See Ross, Martin T. "Structure of the Dynamic Integrated Economy/Energy/Emissions Model: Computable General Equilibrium Component, DIEM-CGE," NI WP 14-12. Durham, NC: Duke University (2014).
[12] See Karplus, Valerie J., Sergey Paltsev, Mustafa Babiker, and John M. Reilly, "Applying Engineering and Fleet Detail to Represent Passenger Vehicle Transport in a Computable General Equilibrium Model," MIT Joint Program on the Science and Policy of Global Change Report No. 216 (April 2012).
[13] See Kishimoto, Paul N., Da Zhang, Xiliang Zhang, and Valerie J. Karplus, "Modeling Regional Transportation Demand in China and the Impacts of a National Carbon Constraint," MIT Joint Program on the Science and Policy of Global Change Report No. 274 (January 2015).

model that can be used to explore climate change mitigation policies including carbon taxes, carbon trading, regulations, and accelerated deployment of energy technology."[14] A bottom-up approach has been constructed for transportation. Total demand for passenger and freight services is projected based on the cost of providing those services, income per capita (in the case of passenger) and total income (for freight), population, and price and income elasticities of demand. Within each service type, market shares among modes and among various technologies are estimated on a logit formulation based on the cost of providing service by the mode or technology. Costs include vehicle purchases, operations cost, and the value of time associated with that mode and technology. Technology market shares also take into account share weights that represent consumer preferences and other factors that have had an impact on historical shares. These weights are derived through calibration or analyst judgment.[15]

[14] Joint Global Change Research Institute, Global Change Assessment Model, www.globalchange.umd.edu/archived-models/gcam/ (accessed August 2016).
[15] Kim, Son H., Jae Edmonds, Josh Lurz, Steven J. Smith, and Marshall Wise, "The objECTS Framework for Integrated Assessment: Hybrid Modeling of Transportation," *The Energy Journal*, 27 (2006).

4. Requirements

The purpose of developing the International Transportation Energy Demand Determinants (ITEDD) model is to create a forecasting tool that tells a plausible mobility story consistent with energy consumption and economic growth patterns across regions. Many mobility stories can be told—all of which have implications for oil and greenhouse gas (GHG) markets. Prescribing the continuation of historic behavior tells a less plausible story as the time horizon expands. The development of ITEDD must be grounded in the questions that the model will most likely need to answer.

Transportation demand, technology choices, and resulting energy consumption can be modeled in many ways. The best option depends on the data and other resources available for analyzing the market. Is city-level detail necessary, or will more aggregate detail be adequate? How far out into the future should the model look? Do vehicle vintages need to be tracked over time? The following questions have been identified as being crucial in terms of model development:

- Is the model solving for the demand by building a demand curve?
- Is the model projecting historical trends into the future?
- Is the model creating a framework for comparing policy alternatives?

In addition, the most important question related to model output is how much of each fuel type is consumed in each of the 16 WEPS+ regions. From this output, resulting GHG emissions and ratios of energy consumption to gross domestic product can be derived.

Answering additional questions requires additional model detail. This thought is a key consideration in the development of the ITEDD model, which is intended to move from a top-level, elasticity-based representation of transportation demand to a more structural, demand-determinant representation. As long as the structure of the model is consistent across successive nested layers, detailed data can be rolled up to higher levels of aggregation.

The output of the ITEDD model should also address the following questions:

- How much energy is consumed for road, rail, marine, and air transportation?
- How much energy is consumed by specific submodes within each of these categories?
- How much energy is consumed by vehicles of specific technology types within submodes?

A variety of questions branch off each of the preceding questions—for example, how many vehicles are needed in each of the above levels? The ability to address each of these more detailed questions must be weighed against the resources and may be limited by data availability.

Switching to the demand side of the market, which drives the consumption of vehicles, we have questions regarding how many people (that is, passengers) are commuting each day and each year. Commuting might include both travel between home and work and home and school. How far do the passengers commute? What percentage of passenger demand is for non-commuting activities? How does population density relate to travel distances? How does the availability of public transit modes relate to distances traveled? These questions are challenging at the country, let alone global, scale.

Freight demand parallels passenger demand in several respects. We may want to know how much freight is shipped, how far it is shipped, and what is shipped. This information requires tracking tons, miles, ton-miles, and vehicle-miles traveled, depending on how we might want to parse and aggregate the data and what data are available. Understanding geographic relationships between originations and destinations for freight might be important when considering where coal-fired power plants are built. Does the coal need to be shipped by rail or converted to electricity and moved by wire? These relationships imply intermodule dynamics, which should be conceived up front but which may not be immediately developed.

As the global oil market becomes tighter and GHG emissions increase, government policies are expected to cast a larger influence on the transportation market worldwide. In order to analyze the potential impacts of different policies, the model will need to have appropriate levers to simulate policies. For example, policy makers might be interested in the impact of assigning a percentage of existing roads to bus rapid-transit in a dense city, which would reduce available road area for private vehicles. The model could show shifts in passenger-miles by each submode, technology, and resulting fuel consumption and emissions. An initial list of policy questions and proposed solutions would inform the model structure that is selected.

One set of policy questions involves U.S. light-duty Corporate Average Fuel Economy and heavy-duty truck fuel economy and GHG emission standards, incentives, and requirements for a number of new technology vehicles, tailpipe airborne emissions (PM, ozone, NOx), and reduction of VMT. Global CO_2 emission targets might also be measured as absolute annual CO_2 emissions and percentage changes from any year (which likely will need to be incorporated into the broader WEPS+ framework). Further, international maritime criteria emissions standards may have an impact on fuel used in marine bunkering.

During discussion of the questions above, some options for model structure were alluded to. For example, if we are only interested in fuel consumption for the transportation sector as a whole, without breakouts for different modes or technologies, then a streamlined model is adequate. However, if we are interested in mode and technology details, we need a different approach. The level of transportation service detail included in the model should support consideration of policies that affect how transportation services are provided in the future. What-if analysis capability is not a model add-on. It is a key design element.

In the transportation sector, energy use provides mobility for either people or goods. Understanding the reasons behind the demand for mobility is important for evaluating future transportation fuel consumption and policies that may alter historical trends in transportation energy use.

For mature transportation systems and for forecasting purposes, the potential for major changes in how transport services are provided may safely be ignored. Modern transportation systems generally evolved in an environment of low and stable prices and matured in an environment when there was perhaps less concern about the national security implications about where the oil was coming from. Urban, suburban, and rural land-based transport services will be met by a mix of private and public vehicles, and that mix will likely remain stable over the next few decades.

The same may not hold true for today's developing economies. In these regions, personal land-based transport may be a long way to say walking or bicycling, and draft animals may play an important role in moving freight. Further, as nations develop, they may become more active participants in global production and consumption of commodities and goods. How transport services are provided in these regions is one of the most important factors affecting oil markets in coming decades. Some combination of factors could evolve to shape a less oil-intensive transportation future. At a minimum, to be useful for policy analysis, a transportation model should be capable of making alternative assumptions about these variables:

- Spatial organization of where people live, work, and play (one way to model this is to apply assumptions about vehicle saturation rates)
- Private versus public mix of transport vehicles (for example, a rapid bus system with dedicated lanes and high-occupancy rates)
- Development of non-oil-based liquid transportation fuels
- Development of plug-in hybrids and pure electric vehicles

Whether implicit or explicit, even a reference case forecast of transportation energy use in 2050 makes assumptions about each of these factors. Back-of-the-envelope calculations are sufficient to indicate the magnitude of the increase in oil supply necessary to fuel high levels of economic growth if the non-OECD nations' transportation systems evolve similarly to the OECD nations'. That is not to say that economic growth will fall far short of expectations. However, transport systems in emerging economies may not be nearly as oil-intensive as the transport systems in today's industrialized nations. A reference case that does not recognize this becomes less and less plausible as the forecast horizon increases.

4.1 Key elements of design

The development of the ITEDD model is constrained by data availability and operational requirements imposed within the current WEPS+ environment. ITEDD will at least need to include these key elements:

- **Activities measured on an annual basis.** This feature is the standard in the WEPS+ modeling environment and the time unit for which all related models communicate with one another.

- **Dynamic structure.** Activities in one year have lasting impacts in subsequent years— for example, a vehicle produced in a given year will remain in the fleet throughout its useful service life. These types of phenomena are typically addressed through multi-period accounting identities or estimated equations with lagged dependent variables.

- **Separate vintages of capital stock.** The model must make a distinction between separate vintages of vehicle stocks for each major mode of transport. Such an accounting structure allows the model to be used to examine policies that affect the new stocks, such as miles per gallon (mpg) standards or specific subsidies in a manner that is separate from consumer behavior.

- **Separate modules for transportation modes (air, marine, road, and rail).** Each major mode of transport will be modeled in a separate module. This structure will allow for further enhancements in related separate modes of transport without disrupting the model's overall structure. Each submodule will have separate equations, but their outputs will all be broken out by fuel type and passenger versus freight designation.

- **Separate modules within transportation modes.** The model would most likely not be structured at this level of detail for all transportation modes, but it should separately represent LDVs, heavy-duty passenger and freight vehicles, passenger and freight rail, air, domestic marine, international marine, and other miscellaneous travel.

- **Include WEPS+ products and related prices.** At a minimum, the model must account for the array of fuel products and associated products that are common across the WEPS+ environment.

The question is not whether the data are readily available to develop a fully detailed service-based model—it will not be; but rather, can the analyst make reasonable and transparent assumptions regarding how energy is currently being used and how this use may change over the forecast period.

4.2 Calibration process

The ITEDD model must have a comprehensive description of how energy is currently being consumed in the transportation sector before it can make any projections. Energy consumed in the transportation sector is consumed in vehicles that provide passenger or freight services measured in units of passenger-miles, vehicle-miles, and ton-miles.[16] The calibration process must provide an estimate of how these transportation services are provided in the calibration year and must account for these initial conditions:

- **Share of fuel by transport mode (road, rail, water, and air)**. For example, what portion of distillate is consumed in road vehicles, locomotives, and marine vessels?

- **Share of fuel consumed by vehicle type**. For example, in the calibration year, how much motor gasoline is consumed in 2- and 3-wheel vehicles, LDVs (cars and light trucks), buses, and trucks? What are the shares of distillate consumed by vehicle type within each mode? For example, what portion of road distillate is consumed in providing passenger transport in buses compared with freight services in heavy trucks?

- **Level of service by vehicle type**. This condition includes two factors for each vehicle type—vehicle efficiency and service intensity.

[16] Pipeline fuel is not considered in this model design. Within the WEPS+ integrating system, pipeline fuel use is calculated as part of oil and natural gas supply.

For the calibration year and for each forecasting year, the following identities must be satisfied:

Modal fuel use = modal travel demand * modal fuel efficiency[17]
Total fuel use = fuel use across all modes
Total travel demand = travel demand across all modes + unmet demand

Summing across all vehicle types yields forecasts of total fuel use and total passenger and freight travel service. Fuel use and travel demand in the first forecast year vary from the calibration year based on changes in explanatory drivers such as GDP. The way in which passenger and freight travel services are provided in the first forecast year, however, is very close to the way they are provided in the calibration year.

Generally, all information is not available for the calibration year, and even in countries where it is, the data are often collected by different government agencies for different purposes. When these data are combined, they cannot be expected to satisfy the identities linking fuel use to transportation services. The art of calibrating a model involves developing a starting point that is both internally consistent (obeys the identities) and makes the best use of the data that are available for the purposes of the model.[18]

Consider passenger travel on buses. Data on the total use of distillate and gasoline in an aggregate road-vehicle category may be available.[19] There may be no breakout by road-vehicle type. Data on the number of buses may be available from vehicle registration data; however, there may be no information on either how many miles these buses traveled or the average number of passengers traveling per bus mile. With this lack of information, it may be tempting to eliminate the detail of a service-based model and develop a model focused on aggregate road-vehicle energy use. But such an aggregation implicitly assumes that each vehicle type maintains its relative share of energy use over the forecast period. For a mature transportation system (and a forecast horizon of less than 20 years), a strong case can be made for such an approach.[20] For the rapidly developing economies of Asia, however, this approach would be a poor assumption. The process of development requires an associated change in the structure of transportation. It may not be reasonable to assume that the role of non-motorized transport remains constant over the forecast, or that the small 3-wheel vehicle will continue as an important road freight vehicle.

[17] Modal travel demand may be expressed in passenger-miles, vehicle-miles, or ton-miles, while modal fuel efficiency may be measured in passenger-miles per Btu, vehicle-miles per gallon, or ton-miles per Btu.
[18] In fact, what is required is that the degree of and reasons for any internal inconsistency remain constant over the forecast period.
[19] See the IEA's *Energy Statistics and Balances for OECD and Non-OECD Nations* and *Energy Statistics and Balances for Non-OECD Nations*, International Energy Agency, Paris, France.
[20] Such an approach would likely provide a fine forecasting model going out 20 years, but unless all road vehicles are assumed to behave in the same way, this approach would not produce a model that could be used to analyze the fuel-use implications of alternative policies.

4.3 Input and output boundaries

ITEDD has two broad types of inputs: those from other WEPS+ elements and those from ITEDD-specific input files. The ITEDD-specific inputs can be further categorized as user inputs or data inputs. User inputs can vary from run to run and will usually be the measures that define model scenarios. Data inputs are not formally fixed and tend to remain stable between model updates. Historical data on transportation-specific variables make up most of the data inputs, as further described in subsequent sections.

ITEDD is designed to operate in the global WEPS+ environment. As such, numerous factors that influence transportation energy demand are set by system elements outside of ITEDD's computational structure or boundary. Macroeconomic- and price-related factors are among the most important inputs into ITEDD from other parts of the WEPS+ environment.

4.4 Reporting requirements

ITEDD must provide three types of outputs. The first are those required to solve the overall WEPS+ modeling structure in the runtime environment. Currently, overall fuel demands are the critical ITEDD-dependent outputs needed for WEPS+ to proceed to convergence, and these fuel demands must be provided in a manner that is responsive to changes in fuel prices and other sectoral demands as the model converges. The second is user-oriented material to support analysis. Vehicle stocks, usage, technology adoption, and fuel use are included in this category. The third are model diagnostics to allow for operational monitoring.

4.5 Data sources

This Component Design Report (CDR) discusses data only to the degree needed to inform the model development process. There will be active and ongoing data acquisition, development, and processing aspects of the ITEDD project. For the CDR, the broad types and categories of data, and their potential limitations, need to be assessed to inform model design decisions.

Missing data that can be developed should be distinguished from data that are unlikely to ever be developed. Data that can be substituted by proxy from other global regions are another distinct category of data availability. The limits and quality of data need to be considered throughout the model development process.

At the same time, careful attention to critical data needs can also provide useful insight into research agendas, which can be shared with stakeholders in the hope that concerted and coordinated effort may yield results on some data needs. As primary users of international energy demand data and other related data, the U.S. Energy Information Administration (EIA) is in a position to inform researchers and other interested parties about the kinds of data that would be of highest priority.

The categories of ITEDD international modeling data are discussed below:

- **Fuel consumption by end-use sector (for example, distillate consumption for transportation uses)**. Fuels included in the ITEDD model are gasoline, distillate, jet fuel, liquid petroleum gas, heavy fuel oil, hydrogen, coal, electricity, and natural gas. The results of the calibration process must produce a forecast fuel consumption series that is consistent with the model calibration year. While this is a projection output requirement for ITEDD, historical data are extremely valuable for calibration, benchmarking, and comparative purposes.

- **Fuel consumption by transportation vehicle type (buses, 2-, and 3-wheel vehicles)**. These data may not be available in most regions. The level of aggregate transportation distillate consumption may be available, but what portions are consumed in cars, buses, heavy trucks, other trucks, city rail, intercity rail, domestic shipping, and international shipping may not be. ITEDD will likely be estimating this information with limited historical data input.

- **Stock of transportation vehicles**. This category includes the number of cars, 2- and 3-wheel vehicles, coal rail cars, locomotives, and aircraft. For most regions, limited information is available for some, but not all, types of vehicles.

- **Passenger activity by mode (road, rail, air, and water) – in units of passenger-miles**. Data may be obtained from estimates of the number and length of passenger trips.

- **Freight activity by mode (road, rail, air, and water) – in units of ton-miles**. Data are often based on records of commerce.

- **Infrastructure in place**. Infrastructure includes the aggregate length of roads by road type (rural-single lane versus highway), the number and capacity of airports, and the length of rail.

- **Annual average travel per vehicle**. Often this variable is a calculated value based on estimates of traffic volume and the stock of vehicles.

- **Vehicle passenger intensity**. The number of passenger-miles per vehicle-mile. Data for average occupancy rates per vehicle-mile for cars and buses may be based on survey information for some regions. Aircraft capacity utilization, or load factor, data are available for many regions. Often, two data series are maintained for aircraft commercial travel—passenger seat-miles and revenue passenger-miles.

  In transportation service-based models, assumptions about vehicle passenger intensity are often the single most important factor in determining results. Which service is more fuel efficient—road travel in a personal car with an average occupancy of two or in a modern rapid bus transit system with an average occupancy of 15 out of 60 seats available?

- **Vehicle efficiency – the number of vehicle miles per unit of fuel**. Vehicle efficiency is often expressed in units of billions of vehicle miles per trillion Btu of fuel. Data on new vehicles are generally available from manufacturers, however, care must be taken to ensure that the data ultimately used correspond to fuel efficiency realized on the road.

5. Solution Methodology

5.1 Modeling approach

As outlined in the related Technical Requirements Analysis, the International Transportation Energy Demand Determinants (ITEDD) model should include the ability to estimate quantities of major liquid fuels consumption to allow WEPS+ to balance global liquid fuel markets. As such, decisions regarding the model's scope and level of representational detail are not only motivated by the availability of data, but also motivated by the importance of the primary design objective.

The specific mathematical representations, choice of parameters, equation specifications, and other elements available for this task, in principle, are unbounded because of the inherently modular design of WEPS+. This flexibility allows the model developers to use a variety of potential examples, new structural elements, and programming techniques to create the model. It is also quite typical for transportation modeling that often employs mixed modeling methodologies to allow for a considerable amount of choice.

In developing the ITEDD model, modelers opted for a structural-based rather than indicator-based conceptual design. However, data and model complexity prevented taking this design concept to the extreme. Instead, a pragmatic balance was struck by focusing on the importance of different vintages of capital stock. Because gasoline is primarily consumed by light-duty vehicles (LDVs), it was also deemed critical to heavily model the details related to LDVs. Heavy-duty vehicles use much of the world's diesel fuel. But LDVs and heavy-duty vehicles are joined by smaller 2- and 3-wheel vehicles, airplanes, locomotives, and marine vessels. When the stock of a particular vehicle class is not explicitly represented in the ITEDD framework, a reduced-form or indicator-based representation is used instead.

As a result, ITEDD is a hybrid structural-indicator model. Nonetheless, the core idea is to use a structural model for key modes of transport and vehicle types to represent indicators such as elasticities or simple travel energy-intensities without resorting to highly aggregate representations. Such indicators can still be calculated from the output of a structural model and can serve as both a check and a means of calibrating a model, but are not the primary building blocks of ITEDD.

5.2 Specific model structure

ITEDD uses a logic flow intended to allow the use of measured data and key demand determinants in both macro and micro contexts. This logic flow has to be carefully specified to maintain consistency and full accounting of travel demand throughout each period's calculations.

ITEDD is set up to operate in a series of steps that are recursive and that aim to work from aggregate to disaggregate representational units and then back again in order to equilibrate the system. The critical logical sequence describes the estimation of travel demand itself, using a set of steps to reflect factors and constraints, including macro and micro (non-population, income, and price) determinants, to:

- Estimate regional-level travel budgets from key population and economic parameters

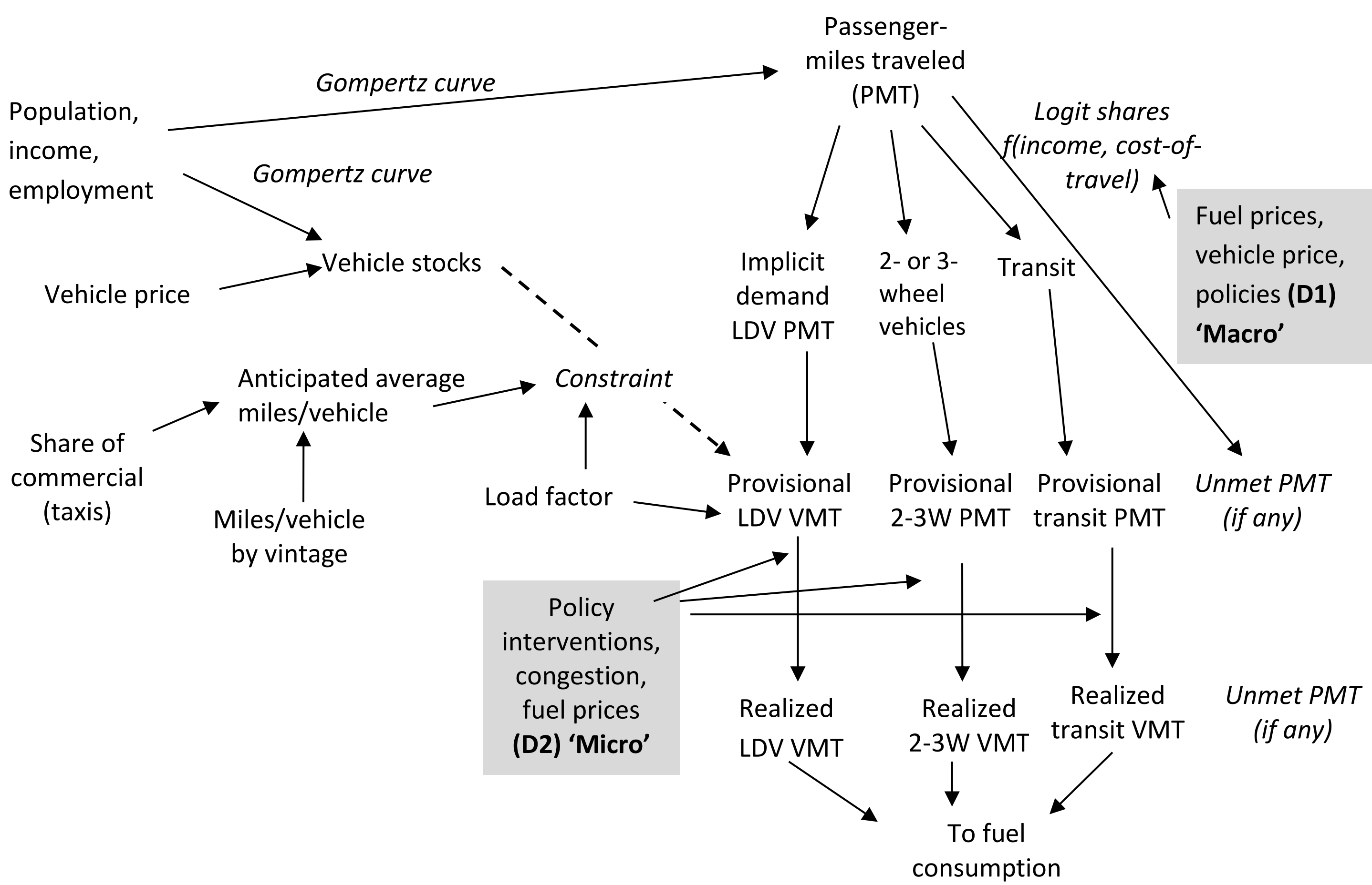
- Estimate implicit demand for each mode of travel, as affected by macro-scale demand determinants
- Estimate provisional demand as the modes are constrained by factors such as vehicle stocks
- Estimate realized demand as is affected by immediate influences, including micro-scale determinants

This conceptual design is partially represented in Table 3 and Figure 2.

Table 3. Overall core model logic

Demand Determinant Category	Subcategory
1. Macro assumptions	1a. Population
	1b. Employment
	1c. Income
2. Initial travel demand budget (VMT for LDVs/ton-miles for freight)	
3. Modal choice (branches to modes) or “implicit demand”	
4. New sales by vehicle class (if class defined for mode)	
5. Vehicle stock profile	
6. VMT per driver or “provisional demand”	
7. Stock utilizations (using set of determinants and reconciled to 3 above) or “realized demand”	

Figure 2. Detailed model conceptual structure, with focus on passenger travel



5.2.1 Mathematical representation

We are developing ITEDD through a multi-step process that involves the introduction of both the regional and representational detail of the model. The model has one prototype region, China, and within the prototype region, the primary emphasis is first on LDV demand. This focus may need to be modified as progress is made and as the prototype is developed into the full, 16-region global WEPS+ transportation module.

Travel demand budget–passenger

Passenger-miles traveled (PMT) is projected using a Gompertz curve formula:

$$PMT = \gamma * e \wedge (\alpha * e\wedge(\beta * GDP/cap)) * Population$$

where

- γ is the maximum PMT per capita, that is, saturation,
- α is a shape factor, that is, x-axis displacement, negative value, and
- β is a shape factor, that is, determines growth rate, negative value.

We use a set of preliminary coefficients for the China prototype. For the global model, a set of four or five curves will likely be used with different coefficients to represent different groups of countries that exhibit different travel patterns (perhaps the United States, Europe, and Japan). The curve for each country will likely need to be shifted to fit the most recent years of historical data.

The total passenger-miles are allocated to modes using a logit function and incorporating the effect of income and the cost-per-mile traveled. The latter may eventually include vehicle costs as well as fuel costs. The initial sharing of passenger-miles is then modified if necessary to accommodate the number of vehicles.

LDV stock and integration with LDV demand

Regional LDV stocks are also projected using Gompertz curves. The saturation parameters are currently user-specified, although they could be modified to be a function of population density and urbanization as in Dargay, et al. (2007),[21] or they could be an input and set by group as for PMT. The economic driver is GDP per capita. A future version might also incorporate vehicle prices, perhaps as in Huo and Wang (2012).[22]

The formulation is the same as for PMT although with different coefficients:

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[21] Dargay, Joyce, Dermot Gately and Martin Sommer, "Vehicle Ownership and Income Growth, Worldwide: 1960-2030," *The Energy Journal* 28, No. 4 (January 2007): 143–170.
[22] Huo, Hong and Michael Wang, "Modeling Future Vehicle Sales and Stock in China," *Energy Policy* 43 (April 2012), 19-21.

$$\text{Light-Duty Vehicle Stock} = \gamma * e \wedge (\alpha * e\wedge(\beta*\text{GDP/cap})) * \text{Population}$$

where

γ is the maximum car ownership per capita, that is, saturation,
α is a shape factor, that is, x-axis displacement, negative value,
β is a shape factor, that is, determines growth rate, negative value, and
GDP/capita could be adjusted for vehicle prices as in the Huo and Wang model or not.

Again, we are using preliminary coefficients for the China prototype. LDV passenger-miles computed from stocks provide a check on the projected LDV share of total passenger-miles. The anticipated miles-traveled per vehicle is based on the average miles per vehicle by vintage and any price or policy effects. We apply an assumed load factor to compute passenger-miles. If we see an insufficient level of stocks to support the projected share of LDV PMT, we adjust the original shared LDV PMT. Presently, the shortfall could be left as unmet demand, but the PMT of the other modes could be adjusted to make up the difference. In this circumstance and absent any price or policy interventions, vehicle-miles traveled (VMT) would be equal to the average of the VMT per vehicle times the vehicle stock. For China, distance traveled per private LDV has fallen over the past several years (Huo et al., 2012),[23] so we have projected an average anticipated distance per vehicle that declines as vehicle ownership increases. In our initial testing version, the projected decline in miles per vehicle is fairly similar to that computed using the miles per vehicle by age vintage provided by Huo and Wang (2012)[24] and the average that would result using the projected vehicle stock by age and current travel per age vintage.

If the projected vehicle stocks indicate higher PMT than the LDV PMT share, then we base the final VMT on the LDV share of PMT divided by the load factor. The resulting VMT/vehicle is lower than the anticipated level. In other words, we would base the final LDV VMT used to compute fuel consumption on the minimum of the stock-based VMT or shared PMT converted to VMT with a load factor.

In developing countries like China, the commercial portion of the LDV fleet is initially significant in size relative to the private vehicle fleet. Commercial vehicles are generally driven longer distances per year and have more rapid scrappage rates. We have therefore separated the commercial from private LDV stocks. For now, we made the simple assumption that the proportion of commercial vehicles will decline to 5% by the year 2040, similarly to that in developed countries.

We compute LDV sales by applying survival rates to prior year stocks. Total sales comprise those necessary to replace retiring vehicles plus those used to satisfy new demands.

$$\text{LDV Sales (t)} = \text{LDV Stock (t)} - \text{Surviving LDV Stock (vintage, t)}$$

Assumptions about vehicle survival rates are taken from Huo and Wang (2012).[25] The probability of survival of a vehicle of age x is expressed as:

[23] Huo, Hong, Qiang Zhang, Kebin He, Zhiliang Yao, and Michael Wang, "Vehicle-use intensity in China: Current status and future trend," *Energy Policy* 43 (April 2012), p. 9.
[24] Ibid., p. 12.
[25] Huo and Wang, p. 23.

Survival (x) = exp[-((x+b)/T)^b]

The Huo and Wang paper provides parameters for b and T for four major regions—China, United States, Europe, and Japan—with Chinese vehicles having much shorter lifetimes than vehicles in other regions. In their scenarios, Huo and Wang allow the China vehicles scrappage rate to evolve over time to values from another region.[26] This flexibility has been included in ITEDD as well. Commercial LDVs are assumed to have scrappage curves with a similar function form, but different parameters.

As described below, vehicle sales are then shared to vehicle types using a logit function and the attributes of each vehicle type. Vehicle sales by type are tracked by vintage with the newest vintage each year being vehicles sold in that year.

LDV fuel economy, fuel shares, and energy consumption

ITEDD contains eight vehicle technology types: gasoline, diesel, natural gas, liquefied petroleum gas (LPG), electric, hydrogen, plug-in hybrids, and other vehicle types. Conventional hybrids are treated as fuel economy improvements within gasoline and diesel vehicles rather than as separate vehicle types. Biofuels are not treated as explicit vehicle types, but rather through blended fuels as determined by the supply side of WEPS+.

The new fuel economy and market shares among vehicle types are related elements. First, fuel economy is projected for each vehicle technology type. Then, using the prior year's market shares among vehicle types, the average fuel economy is computed and compared to the fuel economy standard if any. If the standard is not met, additional fuel economy is added to the various vehicle types, and a pricing adjustment is made among vehicle types that will yield the desired standard.

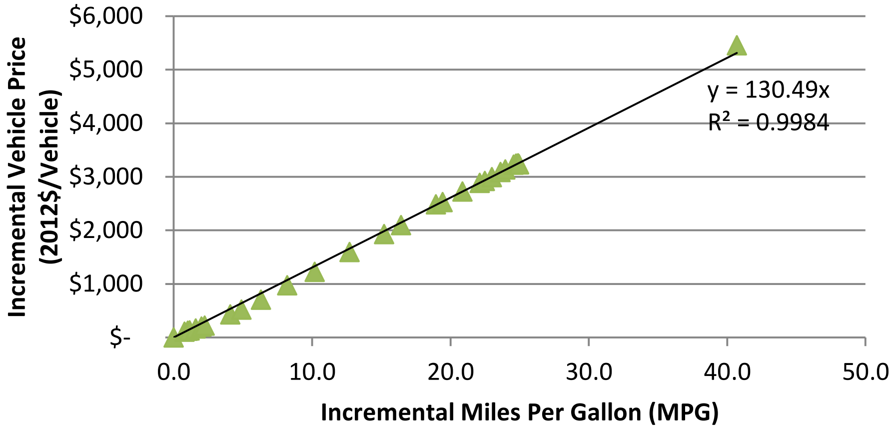
Fuel economy cost curves by vehicle type were derived from a set of scenarios created using the National Energy Modeling System (NEMS). Vehicle prices from a scenario with extended Corporate Average Fuel Economy (CAFE) standards were compared to a case with no standards in order to derive the incremental vehicle price associated with incremental increases in fuel economy. A linear curve was fit with respect to miles per gallon (MPG).

Incremental vehicle price = C * incremental MPG

Note: While linear with respect to MPG, the curve is non-linear with diminishing returns with respect to fuel savings or gallons per mile. In other words, each additional MPG saves less fuel as a vehicle becomes more efficient (Figure 3).

[26] Ibid., p. 23.

Figure 3. Example of fuel economy curve for gasoline light-duty vehicles



Source: EIA using model runs based on the version of NEMS used in the *Annual Energy Outlook 2014*.

Because compressed natural gas (CNG) and LPG vehicles are likely to remain small portions of the vehicle market and their engines are similar to gasoline engines, we assume that manufacturers will produce essentially the same vehicle type for these fuels with the same fuel economy. As a result, the fuel economy of CNG and LPG vehicle types is simply set equal to that of gasoline rather than being independently computed based on those fuel prices.

Electric vehicles have few cost-effective fuel economy opportunities because they are already very efficient, but they are likely to experience cost declines over time as the battery technology improves. These battery cost reductions are a user input that leads to a reduction in the base electric and plug-in hybrid electric vehicle prices over time.

We assume consumers minimize their total LDV transport costs that include the vehicle price and the present value (PV) of lifetime fuel costs. For each vehicle type:

Transport cost = (base vehicle cost + C *(MPG-MPGbase) + (P * L)/(MPG))

where

C is from the MPG curve for that vehicle type
P is the fuel price in $/gallon
L is the PV of lifetime miles

Taking the first derivative and setting it to zero yields:

C - (P * L)*(MPG)^-2 = 0 or MPG =((P * L) / C) ^ 0.5.

The next step is to compute the average MPG across all vehicle types to determine whether fuel economy standards (if any) are met. The weighted average uses the vehicle technology market shares from the prior year as a starting point. If the average MPG is below the standard, then the fuel economy is raised for all vehicle types until the standard is met. This adjustment is accomplished by increasing the marginal cost ($/gallon per mile) of the vehicles with the lowest marginal costs to equal those that are more expensive or until all vehicle types incur the same marginal cost and the standard is met. This approach assumes that vehicle manufacturers try to minimize the cost of compliance.

The marginal cost per gallon per mile is expressed as:

$$(C * MPG)^2.$$

Another method of raising overall fuel economy is to increase the market share of vehicles with high fuel economy while decreasing the share of vehicles with low fuel economy. Manufacturers might accomplish this by adjusting vehicle prices to change the relative attractiveness to consumers. The optimal strategy would be to provide incentives and disincentives based on the same marginal cost of compliance. This strategy is implemented by adjusting retail prices by the amount each vehicle type is above or below the standard times the marginal cost. The net adjustments will be close to zero. A parameter is included that allows the user to scale the price adjustment by a factor of zero to one, in other words, to exclude this effect, include some fraction of this, or include it fully. Early tests suggested that a full inclusion might change the market shares more than desired, so the factor is currently set at 50%.

We project market shares for the vehicle types using a multinomial logit function similar to the one in NEMS, although with a smaller set of attributes: vehicle price, fuel cost per mile, make-and-model availability (MMA), and a constant. The fuel cost per mile takes into account fuel price and the vehicle fuel economy. The MMA represents the concept that new vehicle technologies (such as plug-in hybrid vehicles) are initially offered in limited car models and therefore provide consumers with less choice across other attributes. As a result, the market share will be more limited when the vehicles are first introduced. As the vehicle types gain market share, the MMA increases.

The utility of each vehicle type is expressed as:

$$U_i = \beta_1 * V_i + \beta_2 * CPM_i + \beta_3 * \ln(MMA_i) + \beta_{4i}$$

where

- i is the vehicle type
- V is vehicle price
- CPM is cost per mile
- MMA is make-and-model availability
- β is a shape factor

The market shares are then specified as:

$$S_i = e^{U_i} / \sum e^{U_i}$$

where

- S is the market share for vehicle type i

U is the utility as defined above

After we compute the market shares, we recompute the average fuel economy with the adjusted MPGs to meet the standard. If the shares have changed significantly, the resulting average may overshoot the efficiency standard. Therefore, a small iterative loop repeats the fuel economy calculation using the new market shares and then recomputes the market shares until the average is within the desired tolerance (usually only one or two additional passes).

The vehicle market shares and fuel economies are applied to new vehicle sales each year. We then adjust fuel economy to represent an on-road efficiency that is lower than the rated efficiency. As described above, stock is tracked based on scrappage rates by vintage. The average stock fuel economy for each vehicle type is multiplied by the stock of that type and average VMT per vehicle to yield fuel consumption. With the exception of plug-in hybrid vehicles, there is a direct mapping between vehicle types and fuels. For plug-in hybrid vehicles, we use the electric and gasoline shares of VMT to split total consumption into the two fuels.

For all vehicles except plug-in hybrid vehicles:

$$\text{Fuel}_F = \text{Stock}_T * \text{VMT/vehicle} * \text{avgMPG}_T \;.$$

For plug-in hybrid vehicles:

$$\text{Electricity} = \text{Stock}_T * \text{VMT} * \text{ElectricShare/vehicle} * \text{avgMPGelec}_T$$

$$\text{Gasoline} = \text{Stock}_T * \text{VMT} * (1 - \text{ElectricShare})\text{/vehicle} * \text{avgMPGgas}_T$$

where

F is fuel type corresponding to each vehicle type T.

International marine travel demand, efficiency, and energy consumption

International marine vessels account for an estimated 3% of total global greenhouse gas emissions,[27] and seaborne trade carries 80% of global merchandise trade by volume.[28] International marine energy consumption is a function of travel demand, in this case measured in nautical tonne-miles (ton-miles), and the efficiency of that travel demand movement and is shown as follows:

$$\text{Energy consumption}_{F,R,year} = \textstyle\sum_{C=1,5} (\text{Ton-Miles}_{C,R,year} * \text{Efficiency}_{C,R,year})$$

where

F represents fuel type
R represents WEPS+ region
C represents international trade commodity category (see below)

[27] International Maritime Organization, *Second IMO GHG Study 2009* (July 2009), p. 125.
[28] United Nations Conference on Trade and Development, *Review of Maritime Transport 2013*, UNCTAD/RMT/2013 (December 5, 2013), p. xi.

International maritime ton-miles are reported as a global total by the United Nations Conference on Trade and Development (UNCTAD).[29] These historical ton-mile data are estimated for crude oil, petroleum products, gaseous trade, coal, and all other dry cargos, such as iron ore, grains, containerized merchandise, and vehicles. Because these data are global, other UNCTAD data are used to disaggregate international marine ton-miles by WEPS+ region. These data are given in nominal U.S. dollars and are disaggregated by the following commodities:[30]

- Nonenergy trade
- Coal
- Crude petroleum
- Petroleum products
- Natural gas
- Liquid petroleum gas

Energy commodities (coal, crude, petroleum products, and gaseous products) are taken from UNCTAD data because the WEPS+ model will project the imports and exports by region endogenously, while all other commodities shipped by maritime vessel internationally will be projected based on the value of regional industrial output:

Historical:

$$\text{Ton-miles}_{C,R,year} = \text{Historical Ton-Miles}_{C,global,year}$$

where

R represents WEPS+ region

C represents international trade commodity category

Projected:

For importers:

$$\text{Ton-miles}_{C,R,year} = \text{Ton-Miles}_{C,R,year-1} * ((\text{Commodity Trade Indicator}_{C,R,year}/\text{Commodity Trade Indicator}_{C,R,year-1})$$

For exporters:

$$\text{Ton-miles}_{C,R,year} = \text{Ton-Miles}_{C,R,year-1} + (\text{SumTonMiles}_{C,Ryear} - \text{SumTonMiles}_{C,Ryear-1}) * \text{Share}_{C,R}$$

where

R represents WEPS+ region

C represents international trade commodity category

[29] Ibid., pp. 10–15.

[30] Ibid.

Export tons-miles are set equal to the total ton-miles imported, and the shares are divided among the regions based on historical shares.

The efficiency of these ton-mile movements is taken from the International Maritime Organization (IMO) as a ton-mile weighted efficiency for crude tankers, petroleum product tankers, gaseous tankers, and dry cargo vessels.[31] Projections of efficiencies are a function of the growth in the world oil price.

International marine consumption is then allocated to residual and diesel using the fuel shares. We calculate shares by fuel taking into account that marine heavy oil is a blended fuel (IFO180, or intermediate fuel oil type 180) that is 88% residual oil and 12% distillate oil.

Heavy-duty vehicle, rail, and domestic marine freight travel demand, efficiency, and energy consumption

Energy consumption by heavy-duty vehicle, rail, and domestic marine freight is a function of travel demand, in this case tonne-kilometers, and efficiency:

$$\text{Energy consumption}_{M,R,year} = \text{Tonne-kilometers}_{M,R,year} * \text{Efficiency}_{M,R,year} * \text{Share\_fuel}_{F,R,year}$$

where

M represents the freight mode (heavy-duty vehicle, rail, or domestic marine)
R represents WEPS+ region
F represents the fuel type

Historical tonne-kilometer data are available from the Organization for Economic Cooperation and Development/World Bank for OECD countries, Russia, China, and India, and are estimated from the International Energy Agency Mobility Model (IEA MoMo) data for the remaining regions. Projected freight tonne-kilometer data are calculated as a function of the growth in industrial output by commodity as:

$$\text{Tonne-kilometers}_{M,R,year} = \text{Tonne-kilometers}_{M,R,2012} * (\text{IndustrialOutput}_{M,R,year} / \text{IndustrialOutput}_{M,R,2012})$$

where

M represents the freight mode (heavy-duty vehicle, rail, or domestic marine)
R represents WEPS+ region

Tonne-kilometer data for trucks are then allocated to light-medium heavy-duty trucks (HDTs), medium HDTs, and heavy HDTs, based on shares generated from GDP/population and user-defined coefficients.

Fuel shares for each mode are generated in different ways. For most modes, natural gas fuel shares are generated as a function of the three-year average growth in the difference between diesel and natural gas prices. Each mode's fuel share for other fuels varies.

[31] IMO, *Second IMO GHG Study 2009*, pp. 131 and 144.

For each truck size, we project the change in average MPG using assumed improvement factors relative to projected U.S. MPG improvement values to reflect the amount of U.S.-driven fuel economy improvement that applies to the region. We adjust these truck efficiencies based on changes in fuel price and convert them from MPG to Btu/ton-mile based on load factors and assumed price elasticity coefficients and fuel price growth.

Efficiencies for rail and domestic marine are user specified by year and region.

Air travel

ITEDD uses the air model developed for NEMS, modified to transfer data between Tranair (jet fuel consumption) and ITEDD (GDP and Population) by ITEDD regions.

5.2.2 Combination of modeling methodologies based on international data availability

The set of mathematical representations described for the prototype, single-region version of ITEDD is based generally on the tradeoff between data availability, importance of each option in terms of representational detail, and suitability of specific modeling techniques. This methodology takes advantage of the ability of the modular approach to system modeling in which disparate computational techniques can be employed within the same overall computer simulation system. This philosophy does create risk in terms of how the various parts interact. Some of the specific issues were described in the section on ITEDD detailed structure.

No set guide or method exists to solve the problems or manage the risks inherent in combining modeling techniques within a single dynamic simulation. Instead, a clear procedure for investigating issues is required for identifying key model integration indicators, observing the indicators, diagnosing issues, and pragmatically solving them. Thus for this CDR, identification of the topic is all that we can accomplish, with the modeling team making the necessary adjustments during the model development process. The results, in terms of modifications to the initial ITEDD structure, are reflected in the initial model documentation.

5.3 Calibration and benchmarking

To set up a model, equations need to be parameterized and are often benchmarked with historical data. This data can also assist in setting the initial trajectory for how variables will evolve over time based on how they have evolved in the past.

For calibration and benchmarking, we are processing data from the International Energy Agency's MoMo dataset to use in the ITEDD prototype. These data may also be used to benchmark the full ITEDD model that will be incorporated into WEPS+.

The historical data from the IEA and other sources will be used only to calibrate the prototype model. Although a need to benchmark the final model may arise for reasons of consistency or quality control, it is still useful to let the prototype model perform its estimations without benchmarking at this time. The final version of ITEDD may also be benchmarked to output from the National Energy Modeling System.

5.4 Prototype objectives

The ITEDD project is proceeding in steps, including the development of a single-region prototype before a model that will be developed to cover the 16 regions in WEPS+. This prototype supports the following objectives:

- Understand and test core model logic
- Associate data with the model input and output structures
- Assess the model's computational scale and complexity
- Observe the stability, range, and responsiveness of the prototype model to assess how ITEDD output might integrate with other elements of WEPS+
- Explore analytic topics related to the prototype region

6. Uncertainty and Limitations

We are developing the International Transportation Energy Demand Determinants (ITEDD) model with uncertainty in mind. The emphasis is on the capability to analyze demand determinants in combination, at different points in the model structure, and with a broad treatment of data quality. By using the model logic flow to specify both macro- and micro-level determinants, it should be possible to allow the model to work across a range of conceptual constructs, capturing the issues that affect transportation energy usage and enabling quantification of the issues' potential impacts. At the same time, specific demand determinants, such as policies or constraints, can be left at zero values in order to model others in isolation.

For a robust baseline or reference case, the combination of demand determinants will need to be estimated using analysts' judgment. But, given the uncertainty surrounding the critical issues in transportation energy consumption, it will be the scenario analysis process that provides the greatest value from ITEDD—and from the World Energy Projection System Plus as it is reconfigured in the future. Although it is extremely unlikely for any specific baseline projection to be accurate over long time spans, well-conceived scenario analysis should be able to assess ranges of potential outcomes, levels of risk, and other indicators of interest with regard to the global liquid fuels markets, and their relationships to economic, environmental, and security issues.

7. Conclusions

This Component Design Report (CDR) for the International Transportation Energy Demand Determinants (ITEDD) model of the World Energy Projection System Plus at the U.S. Energy Information Administration provides the technical design basis for model development and is intended to inform and to generate feedback. Final model documentation will be developed as ITEDD is tested and implemented. Interested readers may also find the Technical Requirements Analysis for the ITEDD project to be of interest, as it precedes and informs this CDR.